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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(77)90601-3

Publication date:
1977

STRONG INTERACTION EFFECTS IN ANTIPROTONIC ATOMS

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Received 4 August 1976

We investigate the extent to which antiprotonic atoms provide information on the nucleon-antinucleon interaction.

Recently strong interaction level shifts and widths in antiprotonic atoms have been reported by several groups [1]. In this letter we consider to what extent such measurements can provide information on the $N\bar{N}$ interaction. From the analyses reported to date [2], in which the antiproton-nucleus optical potential is constructed by multiplying an effective scattering length with the nuclear density, it has become apparent that this effective scattering length differs substantially from the free $N\bar{N}$ scattering length. As we shall see below, the dependence of strong interaction level shifts and widths is highly non-linear in the parameters of the $N\bar{N}$ interaction, so that the scattering length times density approximation is not appropriate. Moreover, it appears that it is primarily the level width which is sensitive to the details of the $N\bar{N}$ interaction.

In constructing the antiproton-nucleus optical potential we assume that, at low energy, the $N\bar{N}$ interaction can be described by a local complex potential, for which we use the one of Bryan and Phillips [3]. While somewhat dated, this potential incorporates the essential features we need in studying the dependence on the range and coupling constants.

In the multiple scattering theory of the optical potential various degrees of approximation are possible. In the simplest, the free $N\bar{N}$ scattering length $a = a_R + ia_I$ is multiplied into the nuclear density, $V(r) = -(2\pi/\mu)(1 + (M_{\bar{p}}/M_N))a\rho(r)$, where μ is the $\bar{p}$-nucleus reduced mass, and $M_{\bar{p}}$ and M_N are the $\bar{p}$ and nucleon masses, respectively. In the next approximation one constructs a *local* $N\bar{N}$ t-matrix at threshold, $\tilde{t}(r) = t(r, E = 0)$, and folds it into the density, $V(r) = \int \tilde{t}(r - r')\rho(r')\mathrm{d}^3r'$. The exact treatment of first order multiple scattering would involve using the non-local $N\bar{N}$ t-matrix near threshold to generate the non-local optical potential $V(r, r')$.

The first approximation neglects both the finite range of the $N\bar{N}$ potential and non-locality, the second takes range effects into account, and the third would include both effects. Although the first (scattering length) approximation may be appropriate for pionic atoms (given the relatively short range of the π–N interaction [4]), its use can hardly be justified in antiprotonic atoms since the $N\bar{N}$ interaction contains parts (such as π-exchange) of appreciable range.

To demonstrate the effect of the first two approximations, we have calculated the strong interaction shifts and widths of the 3d level in ^{16}O, experimentally known [1] to be $\Delta E = 60 \pm 76$ eV, $\Gamma = 648 \pm 150$ eV. For the static potential of Bryan and Phillips [3] for which the spin-isospin averaged scattering length is $a = -0.92 + i\,0.70$ we find $\Delta E = 163$ eV, $\Gamma = 149$ eV. Introducing the finite range of the interaction via $\tilde{t}$ gives, $\Delta E = 148$ eV, $\Gamma = 367$ eV. These numbers are the centroid average of the shifts and widths for the two members of the $j = l \pm \frac{1}{2}$ doublet and can be compared directly with the experimental values which were obtained in the same way. The dramatic effect on Γ, in going from the $a\rho$ to the $\tilde{t}$ approximation is the consequence of the finite range of the $N\bar{N}$ extending the optical potential beyond $\rho(r)$, thereby increasing the probability for absorption of the antiproton. In folding $\tilde{t}$ into ρ we have here confined ourselves to the $^3S_1$ channel of $\tilde{t}$. If, as in nuclear matter of effective interaction theory [5] we were to include the ten-

sor force in second order as an additional contribution to an effective central term, the effect on Γ would presumably be enhanced. In view of this sensitivity of level widths to the NN̄ range, any comparison between theory and experiment which ignores the range is likely to be meaningless.

Next we have studied the effect of varying the parameters of the NN̄ interaction (table 1). Here the shifts and widths of each member of the doublet are shown together with the centroid averages ΔE and Γ. We observe once more the insensitivity of the shift and the large changes in the width. Table 1 also demonstrates the highly non-linear character of the solutions, particularly for W_0, the imaginary part of the NN̄ potential. The large increase in Γ, which accompanies an increase in the coupling constants g^2, can easily be understood as following from the fact that the real part of the NN̄ potential is attractive; increasing this attraction pulls the antiproton into the nucleus and thus, once more, increases its probability for absorption.

We have also examined some other factors which could obscure the analysis of strong interaction effects to determine the extent to which they do so. (i) Whereas the proton distribution can be determined from

Table 1
Sensitivity of level shifts and widths (in eV) to variations in the NN̄ potential The parameters of the nuclear density are taken from ref. [6]. g_{σ_0}, g_ω, are the NNσ_0, NNω, .. coupling constants. W_0 is the strength of the imaginary part of the potential. The superscripts refer to the $j = l \pm \frac{1}{2}$ components of the doublet. ΔE and Γ are the centroid average shift and width.

		ΔE^+	ΔE^-	ΔE	Γ^+	Γ^-	Γ
$\bar{a}\rho$		165	161	163	151	148	149
$\tilde{t}$		150	146	148	369	363	367
$g^2_{\sigma_0}$	× 2	164	160	153	434	427	431
	÷ 2	140	137	139	324	319	322
$g^2_{\sigma_0}, g^2_\omega$	× 2	153	150	152	475	467	471
	− 2	119	116	118	318	312	315
all g^2	× 2	204	199	202	751	740	747
	÷ 2	136	133	135	225	221	224
W_0	× 2	138	135	137	334	328	331
	− 2	173	169	171	329	324	327

Table 2
Sensitivity of level shifts and widths (in eV) to (i) changes in the density, (ii) strong spin-orbit potential, (iii) analytically continuing $\tilde{t}$.

	Density from	$\langle r^2\rangle^{1/2}$	ΔE^+	ΔE^-	ΔE	Γ^+	Γ^-	Γ
without strong l, s	Ref. [6]	2 89	150	146	148	369	363	367
without strong l, s	Ref. [1]	2 74	115	112	114	328	322	326
without strong l, s	Ref. [7]	2.71	97	95	96	310	304	307
with strong l, s	Ref. [6]	2.89	160	130	148	354	388	368
with strong l, s	Ref. [1]	2.74	124	99	114	315	345	327
$k = k_B = 1$ 0.087	Ref. [6]	2.89	160	156	158	388	382	386

Table 3
Comparison between level shifts and widths calculated with ($\tilde{t}$) and without finite ($a\rho$) range correction

Nucleus	Level	$a\rho$		$\tilde{t}$		Exp	
		ΔE	Γ	ΔE	Γ	ΔE	Γ
^{14}N	3d	59	57	51	141	39 ± 51	173 ± 34
^{16}O	3d	163	149	148	367	60 ± 72	648 ± 150
^{32}S	4f	168	165	130	457	80 ± 40 41 ± 44	310 ± 180 [1] 760 ± 110 [2]

electron scattering and muonic X-ray data, less is known about the neutron distribution. In table 2, shifts and widths are given for some of the density distributions used to data. (ii) In addition to the electromagnetic Thomas term, the strong interaction itself can give rise to a spin-orbit term in the optical potential [6] (even in spin saturated nuclei). The effect of this term is to reduce the splitting of the doublet (by $\approx$30 eV if we use the parameters of ref. [6]). It does not, however, appreciably affect the widths (table 2). (iii) Since the antiproton is in a bound orbit with $E_B < 0$, we have repeated the calculation with $\tilde{t}(r, E = 0)$ replaced by $\tilde{t}(r, E_B)$, i.e. analytically continuing $\tilde{t}, E \to E_B, k \to ik_B$. For $E_B = -167$ keV, we find $\Delta E = 158$ eV, $\Gamma = 386$ eV, compared with the values given above, $\Delta E = 148$ eV, $\Gamma = 367$ eV.

Finally, since it appears that the main deviation from the $a\rho$ approximation comes from the range of the $N\bar{N}$ interaction, we have calculated shifts and widths in other nuclei, using the static Bryan-Phillips potential, with and without finite range effects (table 3). The comparison with experiment indicates that the reported large discrepancies between the measured widths and those calculated in the $a\rho$ approximation [1, 2] may be due to the neglect of the finite range of the $N\bar{N}$ interaction, and not necessarily to an inadequacy of the $N\bar{N}$ interaction.

This work was performed as part of the research program of the "Stichting voor Fundamentaal Onderzoek der Materie" (F.O.M.) with financial support from the "Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek" (Z.W.O.).

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